2

SEISMIC VULNERABILITY OF BUILDINGS

2.0 INTRODUCTION

This chapter describes the general characteristics of all structural materials and systems (i.e., strength, stiffness, ductility, and damping) and the design and construction features that may adversely affect the seismic performance of a structure. Since an informed decision regarding the most cost-effective techniques for rehabilitating an existing structure to resist seismic forces requires an understanding of the structural system or combination of systems that resist the lateral loads, the advantages or disadvantages associated with the physical attributes of the systems and the constraints on system performance due to adverse design or construction features, the emphasis here is on the complete structural system. Chapter 3 focuses on techniques to strengthen the three principal lateral-force-resisting subsystems (vertical-resisting elements, diaphragms, and foundations) and the connections between these subsystems. Chapter 4 identifies methods to rehabilitate structures by reducing demand.

2.1 GENERAL ATTRIBUTES OF STRUCTURES

Strength, stiffness, ductility, and damping govern the dynamic response of a structure to ground motion. An ideal structure would rate highly with respect to all of these attributes; however, this is seldom the case even in new construction and may be impossible to achieve when strengthening an existing structure. Fortunately, these attributes are interrelated, and it is usually possible to compensate for a deficiency in one by enhancing one or more of the others (e.g., additional strength and stiffness may compensate for low ductility and damping, a subject discussed in Chapter 4).

2.1.1 STRENGTH

The most obvious, although not necessarily the most important, consideration in seismic rehabilitation is strength. A seismically weak structure can be rehabilitated by strengthening existing members or by adding new members that increase the overall strength of the structure. Many of the rehabilitation techniques presented in this handbook are aimed at increasing strength, and informed identification of the building elements that should be strengthened can lead to significant cost savings in an upgrading scheme.

2.1.2 STIFFNESS

As indicated by the base shear formula in the 1988 *NEHRP Recommended Provisions*, structural stiffening that reduces the fundamental period of the building may result in higher seismic forces to be resisted by the building. Nonetheless, additional stiffening generally will reduce the potential for seismic damage. Drift limitations specified by most building codes are intended to provide for minimum structural stiffness.

Transfer of loads among the elements of a structure depends on the relative stiffness of those elements. To select the most appropriate technique for seismically rehabilitating a structure, it is important to evaluate the stiffness of both the existing elements and those to be added to ensure that the seismic load path is not altered in a way that creates new problems. To contribute effectively, an added element must be stiff enough relative to the existing lateral-force-resisting elements to attract sufficient load away from the existing system. The location of an added member and, therefore, the added stiffness it contributes also is important. The engineer

should attempt to locate new elements in such a way as to minimize eccentricities in the building and limit torsional responses.

2.1.3 DUCTILITY

The ductility of a structure or element (i.e., the ability of the structure or element to dissipate energy inelastically when displaced beyond its elastic limit without a significant loss in load carrying capacity) is an extremely important consideration in seismic rehabilitation. The structural properties of some materials have a post-elastic behavior that fits the classic definition of ductility (i.e., they have a near-plastic yield zone and this behavior is reasonably maintained under cyclic loading). Other materials such as reinforced concrete and masonry, nailed wood systems, braced frames, and floor diaphragms have stiffness degradation and may even exhibit a pinched load-displacement relationship when subjected to cyclic loading. The hysteretic damping of these materials may not increase as is common for the elastic-plastic behavior but the stiffness degradation has a beneficial influence similar to an increase in damping in that the base shear of the system is reduced. However, the interstory and total relative displacement of the stiffness degrading structure or element is significantly increased. Control of relative displacement of this class of structure or element is of prime importance.

2.1.4 DAMPING

During an earthquake, a structure will amplify the base ground motion. The ground motion at the base includes the amplification caused by soil profile type through the inclusion of a soil profile coefficient in the base shear formula. The degree of structural amplification of the ground motion at the base of the building is limited by structural damping or the ability of the structural system to dissipate the energy of the earthquake ground-shaking. The differences in the response modification coefficient (R) and the deflection amplification factor (C_d) of Table 3-2 of the 1988 *NEHRP Recommended Provisions* are partially due to an estimation of probable structural damping of greater than 5 percent of critical.

2.2 ADVERSE DESIGN AND CONSTRUCTION FEATURES

A number of design and construction features have an adverse impact on structural response by precluding the effective development of the capacity of the various structural components.

2.2.1 LACK OF DIRECT LOAD PATH

An adequate load path is the most essential requirement for seismic resistance in a building. There must be a lateral-force-resisting system that forms a direct load path between the foundation, the vertical elements, and all diaphragm levels and that ties all portions of the building together. The load path must be complete and sufficiently strong. The general path is as follows:

- Earthquake inertia forces, which originate in all elements of a building, are delivered through structural connections to horizontal diaphragms;

- The diaphragms distribute these forces to vertical components of the lateral-force-resisting system such as shear walls and frames;

- The vertical elements transfer the forces into the foundation; and

- The foundation transfers the forces into the ground.

The load path therefore consists of elements within and between the following subsystems: vertical-resisting elements, diaphragms, and foundations.

2.2.2 IRREGULARITIES

Most building codes prescribe seismic design forces that are only a fraction of the forces that would be imposed on a linearly elastic structure by a severe earthquake. These codes therefore imply that the inelastic response of the designed structures is required to fulfill the primary performance objective (i.e., preserve life safety by precluding structural collapse). The equivalent static lateral loads and design coefficients prescribed by the codes are necessarily imperfect approximations of the nonlinear dynamic response of code-designed regular structures. Vertical and plan irregularities can result in loads and deformations significantly different from those assumed by the equivalent static procedures. It is most important for the engineer to understand that severe irregularities can create uncertainties in the ability of the structure to meet the stated performance objectives. Irregular conditions exist, to some degree, in most buildings. Minor irregularities have little or no detrimental effect on structural response. Guidelines for the evaluation of the significance of the vertical and horizontal or plan irregularities are provided in the *NEHRP Evaluation Handbook*). If a significant irregular condition cannot be avoided or eliminated by design changes, the designer should both comply with any special provisions prescribed by the code and consider the ability of the structure to avoid collapse when subjected to relative displacements that may be several times greater than the anticipated nonlinear displacements.

2.2.2.1 Vertical Irregularities

The vertical irregularities that may adversely affect a building's seismic resistance are discussed briefly below.

Stiffness irregularity results when one or more stories are significantly softer (i.e., will be subject to larger deformations) than the stories directly above.

Weight or mass irregularity occurs when the effective mass (i.e., weight divided by the acceleration due to gravity) of any story is substantially greater than the effective mass of an adjacent story.

Vertical geometric irregularity results from building setbacks or elevational discontinuities (i.e., when the upper portions of a building are reduced in plan area with respect to the lower portions).

Vertical discontinuity in capacity occurs when the story strength in a story is significantly less than that in the story above. The story strength is defined as the total strength of all the seismic-resisting elements sharing the story shear for the direction under consideration.

Vertical discontinuity in load path is a condition where the elements resisting lateral forces (i.e., moment frames, shear walls, or braced frames) are not continuous from one floor to the next. Figure 2.2.2.1 shows two common examples. The upper sketch shows an "out-of-plane" vertical discontinuity that causes the vertical load path to be discontinuous. In the upper sketch, the shear walls of the second and third stories are exterior shear walls while the shear walls in the first floor are interior walls. The seismic forces from the top two stories must be transferred through the second floor diaphragm and then into the first floor shear wall. The discontinuity results in very high forces on the diaphragm. The lower sketch in Figure 2.2.2.1 is an example of an in-plane discontinuity with a potential for overturning forces in excess of the capacity of the column.

The usual deficiency in the diaphragm is inadequate shear capacity. Unlike typical floor diaphragms that need only transfer tributary seismic floor shears, the diaphragm at the base of a discontinuous shear wall must transfer the cumulative seismic shears in the shear wall from all of the levels above the discontinuity. A typical cause of distress in concrete columns at the ends of discontinuous shear walls is inadequate capacity to resist the overturning loads from the discontinuous wall above. For many years, seismic provisions in building codes have prescribed factored design loads for shear walls that were in excess of those required for columns. Thus, in a severe earthquake, the discontinuous shear wall was capable of generating overturning forces in excess of the capacity of the supporting columns. During the 1979 Imperial County Earthquake in California, the 6-story County Services Building was irreparably damaged when a number of the first story columns under discontinuous shear walls collapsed due to excessive overturning forces. As a result of that earthquake, current code provisions discourage vertical discontinuities and require special strengthening of columns if the discontinuities cannot be avoided.
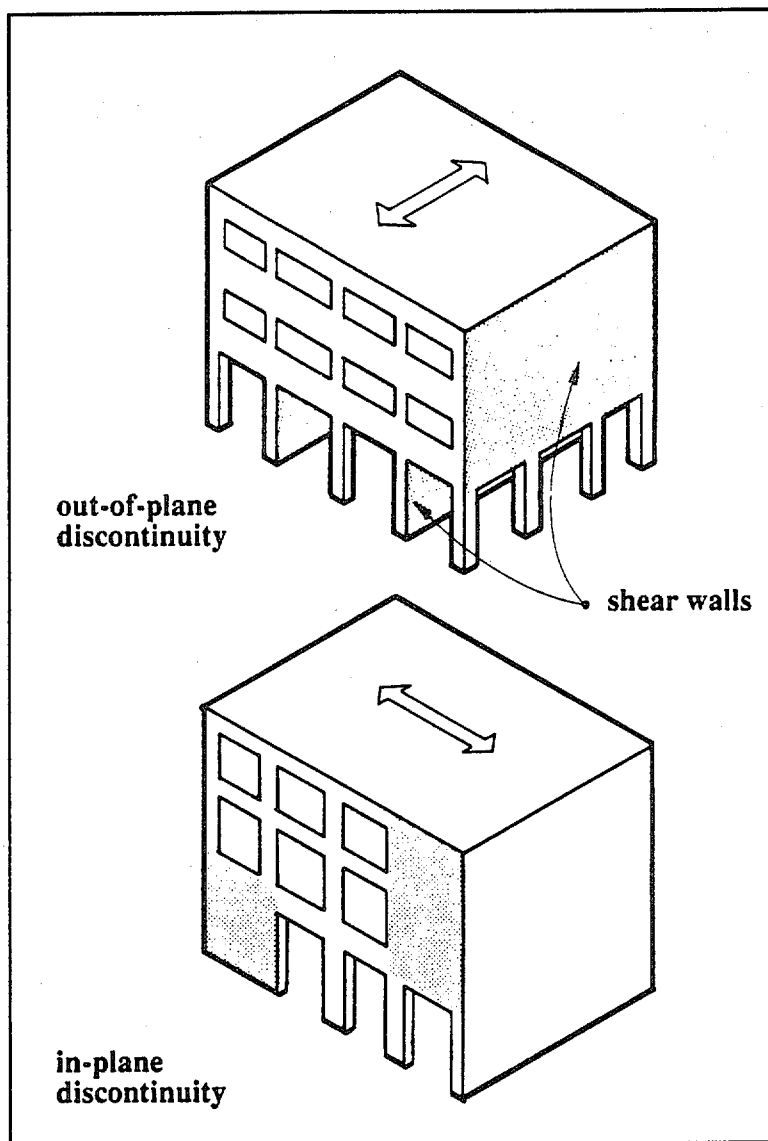
7

out-of-plane
discontinuity

shear walls

in-plane
discontinuity

FIGURE 2.2.2.1 Vertical irregularities--examples of in-plane and out-of-plane discontinuities.

2.2.2.2 Rehabilitation Techniques for Vertical Irregularities

The obvious remedial technique for any irregularity is to modify the existing structural elements or add new structural elements to eliminate or significantly reduce the irregularity. The engineer must take special care to avoid creating greater or new problems in the existing elements. For example, if vertical bracing is used to increase the strength of a weak story, it is important to determine the effect that this modification will have on the story stiffness (i.e., whether it will create a soft story condition in the stories below), whether it will create significant torsional eccentricity (see Sec. 2.2.2.3), and/or whether the load path in the diaphragms above and below will be adequate for the revised distribution and transfer of the shear forces. If a new shear wall is added in a shear wall building to increase story strength or stiffness, the same concerns must be investigated. Extending the new shear wall to the foundation level is one way to avoid the vertical discontinuity. Vertical supports below the wall also should be investigated to determine their capacity to resist realistic overturning forces.

It may not be feasible to eliminate or reduce some weight or mass irregularities (e.g., a heavy boiler extending through several stories of an industrial building) or elevational irregularities (e.g., building setbacks). If the irregularity cannot be eliminated or significantly reduced, a dynamic analysis that will better represent the structural response may be required to identify the appropriate location for needed strengthening and its extent.

A common technique for improving the seismic performance of structures with vertical discontinuities in load path is to strengthen the columns below the discontinuity (with methods such as those discussed in Chapter 3) so that they can resist the vertical forces that can be imposed by overturning moments of the above walls. The diaphragm spanning between the discontinuous vertical-resisting elements also may require strengthening. Alternatively, the discontinuity can be eliminated of new vertical-resisting elements are built directly below the existing vertical-resisting elements; however, the effect the new members will have on the functional space of the building must be evaluated.

2.2.2.3 Horizontal or Plan Irregularities

Plan structural irregularities in buildings that may adversely affect a building's seismic resistance are discussed briefly below.

Torsional irregularity occurs in buildings with rigid diaphragms when the center of mass in any story is eccentric with respect to the center of rigidity of the vertical lateral-load-resisting elements. Nominal eccentricity, or torsion, is common in most buildings and many building codes require that an accidental eccentricity (usually prescribed as 5 percent of the maximum plan dimension) be added to the actual computed eccentricity to determine the torsional forces. An exception occurs when a floor or roof diaphragm is relatively flexible with respect to the vertical lateral-load-resisting elements (e.g., a nailed wood diaphragm in a building with concrete or masonry shear walls). In this case, the vertical elements are assumed to resist only tributary seismic loads. Note that by making this assumption the effects of torsion may be neglected. In some cases (e.g., steel floor or roof decking in a building with steel moment frames), the relative rigidity of the diaphragm may be difficult to assess and the designer may elect to distribute the seismic loads on the basis of a rigid diaphragm and by tributary area and then to use the more conservative results from the two methods.

Re-entrant corners in the plan configuration of an existing structure (and its lateral-force-resisting system) create excessive shear stresses at the corner.

Diaphragm discontinuity occurs when a diaphragm has abrupt discontinuities or variations in stiffness. A common diaphragm discontinuity is split level floors. Unless proper members exist either to transfer the diaphragm forces between the split levels or to independently transfer the forces via vertical members to the foundation, damage is likely to occur at the interface. This condition also exists when diaphragms have large cutout or open areas or substantial changes in effective diaphragm stiffness from one story to the next.

Nonparallel systems is the condition that occurs when the vertical lateral-force-resisting elements are not parallel to or symmetric about the major orthogonal axes of the lateral-force-resisting system.

2.2.2.4 Rehabilitation Techniques for Horizontal Irregularities

The seismic rehabilitation of a structure with a large eccentricity, due either to the distribution of the vertical-resisting elements or the distribution of the mass in the building, is best accomplished by reducing the eccentricity. Locating stiff resisting elements that reduce the eccentricity (Figure 2.2.2.4a) reduces the forces and stresses due to torsion and increases the lateral-force-resisting capacity of the entire structure. The seismic deformations of the entire structure also are significantly reduced by strategically locating the new walls to minimize torsion. The most direct rehabilitation technique for excessive shear stresses at a re-entrant corner is to provide drag struts to distribute the local concentrated forces into the diaphragm (Figure 2.2.2.4b). Other alternatives include strengthening the diaphragm with overlays and reducing the loads on the diaphragm by providing additional vertical-resisting elements.

Diaphragm discontinuities due to abrupt changes in stiffness can be improved by developing a gradual transition through selective stiffening of the diaphragm segments adjacent to the stiff elements. Stress concentrations in the diaphragm at the corners of large openings can be reduced by providing collector members or drag struts to distribute the forces into the diaphragm.

Improving deficient conditions caused by diaphragm discontinuities (such as may be present in split level framing) can be accomplished by providing an adequate load path for the lateral forces. Figure 2.2.2.4c illustrates strengthening techniques for a split level floor diaphragm in typical residential construction. The figure shows two existing diaphragms at an interior cripple stud wall. The deficiency is the lack of a direct force path for diaphragm shears normal to the plane of the figure. The new construction provides vertical sheathing, blocking, and appropriate nailing to transfer the shears from both diaphragms to the foundation. For additional information and connection details for addressing split level conditions in wood frame construction see *The Home Builder's Guide for Earthquake Design* by (Shapiro, Okino, Hom and Associates, 1980).

Structures with nonparallel systems can be strengthened by ensuring that there is an adequate load path for the various force components resulting from the transfer of shears from the diaphragm to the vertical lateral-load-resisting systems. A structure with a nonparallel system is shown in Figure 2.2.2.4d. Providing a drag strut at the corner as indicated will distribute into the diaphragm the out-of-plane force component at the intersection of the two shear walls.
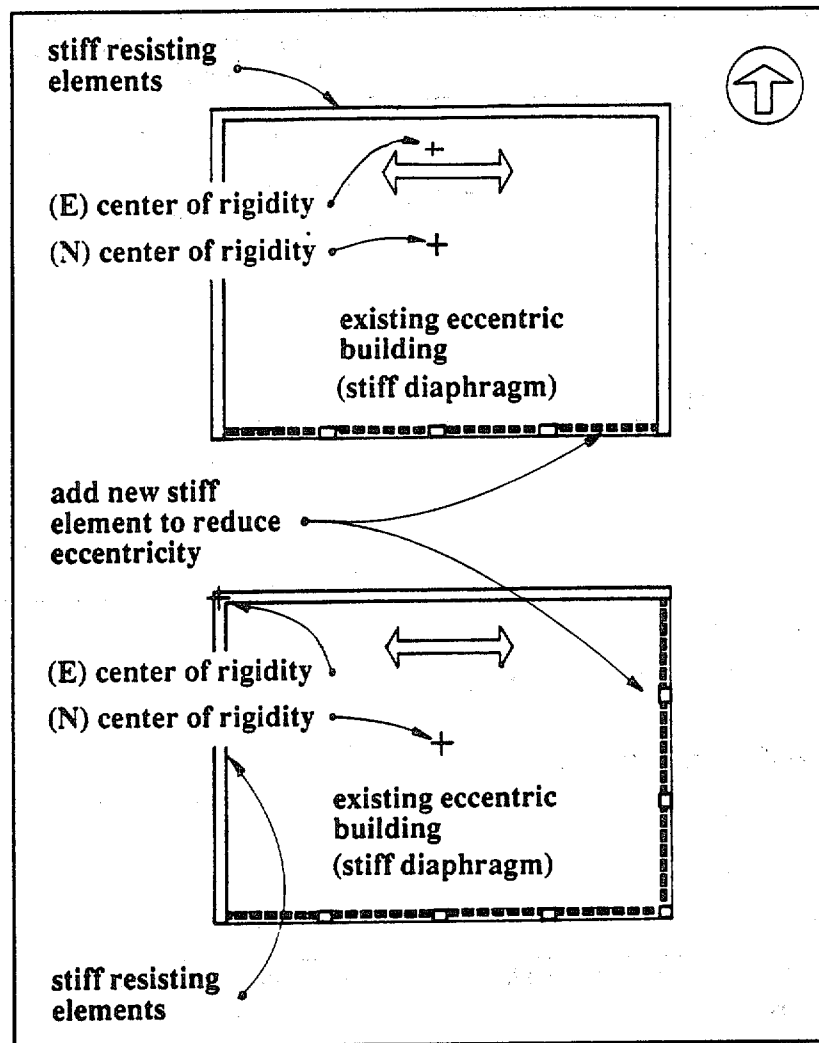
9

stiff resisting
elements

(E) center of rigidity

(N) center of rigidity

existing eccentric
building
(stiff diaphragm)

add new stiff
element to reduce
eccentricity

(E) center of rigidity

(N) center of rigidity

existing eccentric
building
(stiff diaphragm)

stiff resisting
elements

FIGURE 2.2.2.4a   Horizontal or plan irregularities--rehabilitating a structure to reduce torsional loads.
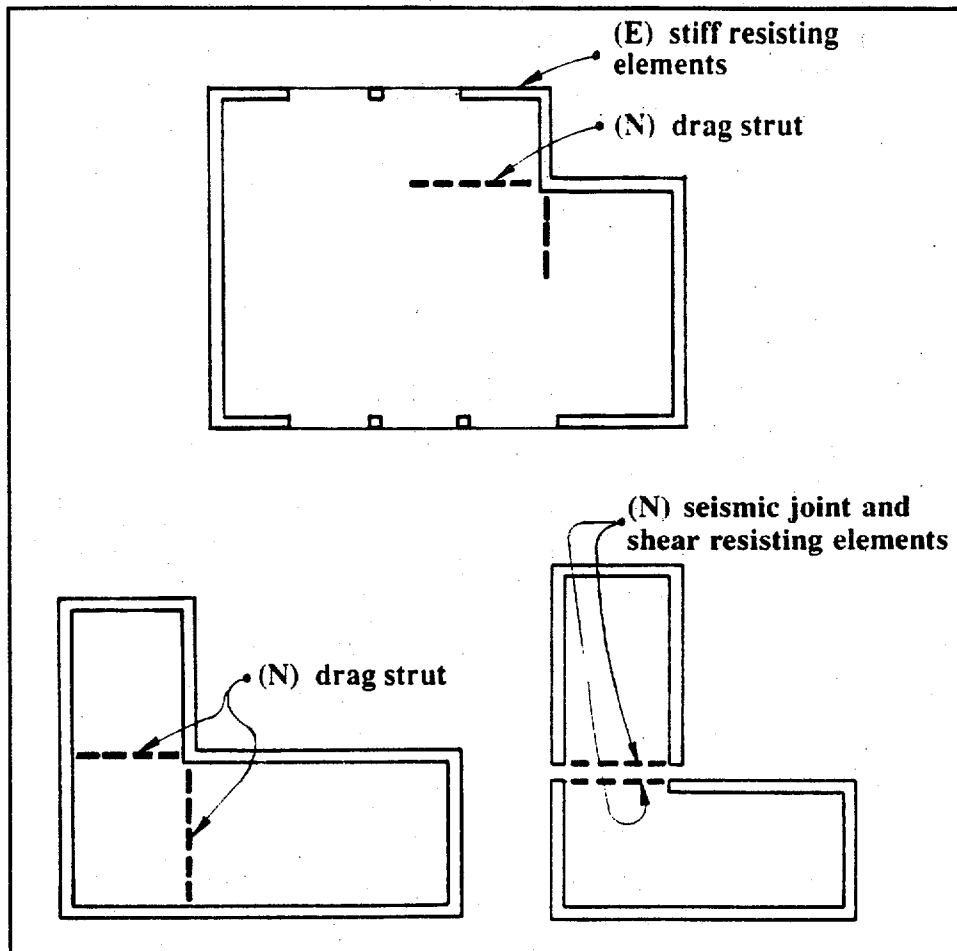
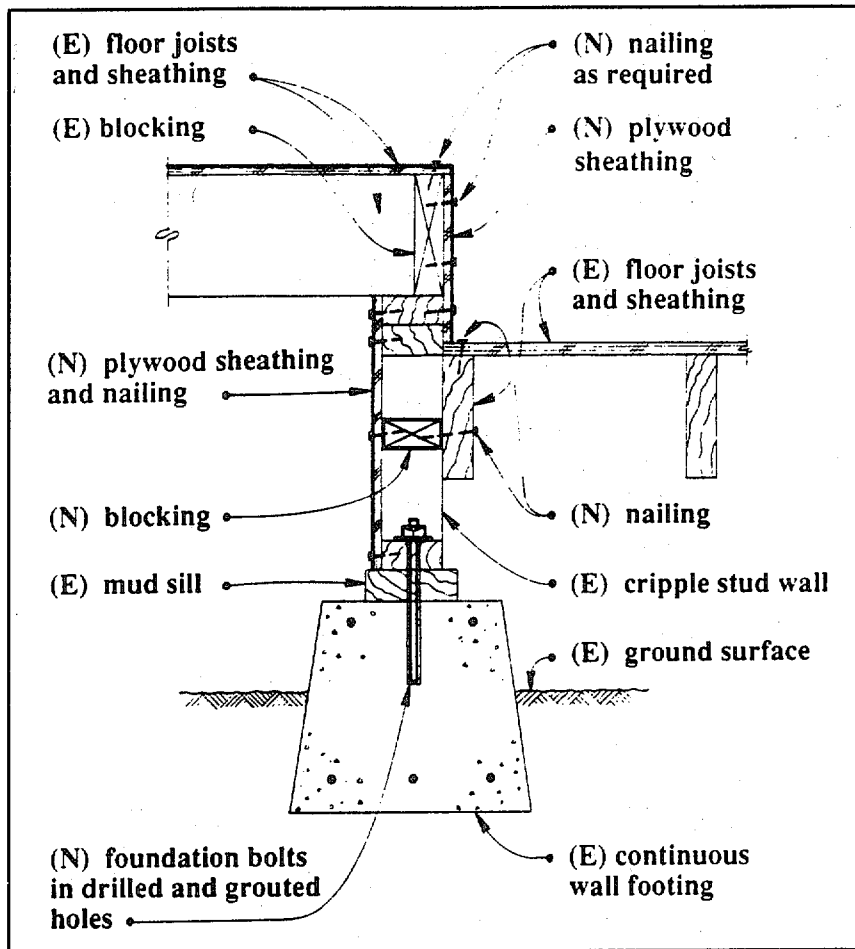**FIGURE 2.2.2.4b Horizontal or plan irregularities--rehabilitating buildings with re-entrant corners.**

11

(E) floor joists and sheathing

(E) blocking

(N) nailing as required

(N) plywood sheathing

(E) floor joists and sheathing

(N) plywood sheathing and nailing

(N) blocking

(N) nailing

(E) mud sill

(E) cripple stud wall

(E) ground surface

(N) foundation bolts in drilled and grouted holes

(E) continuous wall footing

FIGURE 2.2.2.4c Horizontal or plan irregularities--example of strengthening a split level diaphragm.

wall motion
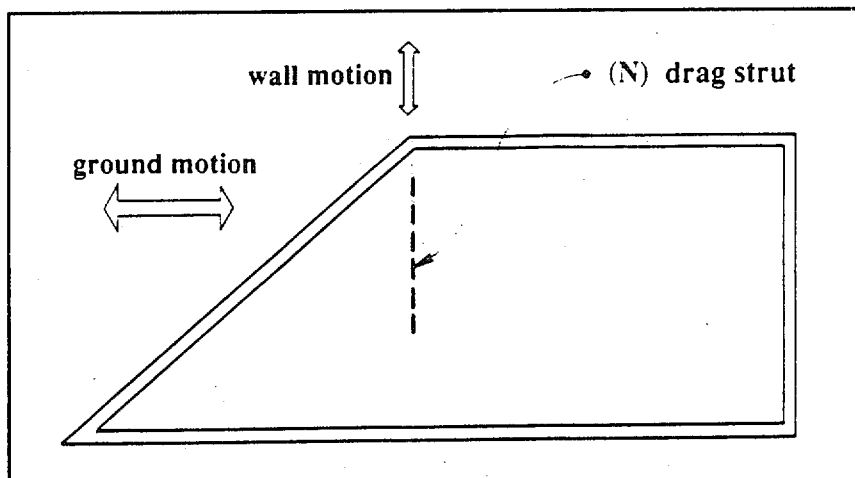
(N) drag strut

ground motion

FIGURE 2.2.2.4d Horizontal or plan irregularities--rehabilitating building with nonparallel systems.

2.2.2.5 Reduction of Irregularities and Re-Analysis

The irregularities discussed above will affect the dynamic response of a structure to seismic ground motion and may invalidate the approximation made in the code-prescribed equivalent static lateral force analysis. The *NEHRP Evaluation Handbook* presents thresholds at which these effects may be considered significant but they are necessarily subjective and should be used with judgment, particularly when a structure has more than one of the above irregularities. Although a linear elastic dynamic analysis will help to identify the location and extent of the irregular responses, any analysis is subject to the validity of the model and, for an existing structure, there may be many uncertainties in the modeling assumptions. Also, as indicated above, the uncertainties associated with the extrapolation of results of linear elastic analyses to obtain estimates of nonlinear response increase greatly when the structure is highly irregular or asymmetrical. For these reasons, structural modifications associated with seismic upgrading of an irregular building should aim primarily to eliminate or significantly reduce the irregularity. The illustration in the lower portion of Figure 2.2.2.4b is an example of an irregular building divided into two separate, regular structures by providing a seismic separation joint. This concept requires careful structural and architectural detailing at the separation joint and may not be cost-effective as a retrofit measure except in cases where extensive alterations are planned for other reasons (e.g., an industrial structure being converted to light commercial or residential use).

Although the structural modifications described above to eliminate or reduce irregularities are intended to improve a structure's dynamic response and to increase its capacity to resist seismic forces, in some cases the modifications may shorten the building's period thereby increasing the seismic demand on the structure. For this reason, and also to evaluate the redistribution effects of any significant modifications, it is recommended a re-analysis be performed to identify the need for any additional modifications.

2.2.3 LACK OF REDUNDANCY

2.2.3.1 The Problem

Structures that feature multiple load paths are said to be redundant. Loads producing temporary seismic overstress of individual members or connections in a redundant structure may be redistributed to alternate load paths with the capacity to resist these seismic loads. The seismic capacity of structures that lack redundancy is dependent on adequate nonlinear behavior of the lateral-load-resisting elements. Engineering judgment should be used to ascertain the need for redundancy.

2.2.3.2 Rehabilitation Techniques for Lack of Redundancy

Rehabilitation techniques that enhance redundancy generally involve the addition of new lateral-load-resisting elements or new systems to supplement existing weak or brittle systems. For example, the addition of new steel braced frames or reinforced concrete shear walls in an existing concrete frame building will provide redundancy to the existing system. The relative rigidity of the new systems probably will dictate that little or none of the design lateral loads be resisted by the existing concrete frame, but if the new braced frames or shear walls are properly designed for ductile behavior as they yield in a severe earthquake, the lateral loads will be redistributed to take advantage of the capacity of the existing concrete frames. This example illustrates that ductility and an adequate load path are essential to the redistribution of loads in redundant systems.

2.2.4 LACK OF TOUGHNESS

2.2.4.1 The Problem

Toughness is defined here as the ability of a structure to maintain its integrity and preclude collapse during a severe earthquake that may cause significant structural damage.

2.2.4.2 Rehabilitation Techniques for Lack of Toughness

Existing connection details and those for new structural modifications should be evaluated for toughness. Although Chapter 3 identifies some techniques for strengthening connection deficiencies, the engineer must further evaluate these connections in terms of their performance under extreme structural loads and deformations. Codes may prescribe that some precautions be taken (e.g., oversizing connection requirements to avoid premature failure of bracing members and evaluating the deformation compatibility of vertical load-resisting members that are not part of the lateral-load-resisting system); however, other considerations (e.g., avoiding weld configurations that could lead to prying action or other stress concentrations) require engineering judgment. For some structural systems (e.g., steel moment frames), providing additional strength in the connections will increase the toughness of the system; however, in other systems (e.g., concrete moment frames), lack of toughness may require displacement control through the addition of stiffer elements or supplemental damping to protect the existing system.

2.2.5 ADJACENT BUILDINGS

2.2.5.1 The Problem

When the gap between buildings is insufficient to accommodate the combined seismic deformations of the buildings, both may be vulnerable to structural damage from the "pounding" action that results when the two collide. This condition is particularly severe when the floor levels of the two buildings do not match and the stiff floor framing of one building impacts on the more fragile walls or columns of the adjacent building.

2.2.5.2 Rehabilitation Techniques for Potential Impact from Adjacent Buildings

Since the gap between two buildings usually cannot be increased, increasing the stiffness of one or both buildings may reduce the seismic deformations to the point where impact is precluded with the existing gap. This technique, however, may not be feasible for stiff shear wall buildings of concrete or masonry and, for those cases, consideration should be given to providing alternative load paths for the vertical load-resisting members (i.e., bearing walls or columns) that may be damaged or destroyed by the impact. These alternative load paths would include supplementary columns or vertical shoring to support the floor or roof systems. These supplementary supports would be installed at sufficient distance from the vulnerable exterior walls or columns to be protected when the existing elements are damaged.

2.3 DETERIORATED CONDITION OF STRUCTURAL MATERIALS

2.3.1 THE PROBLEM

Structural materials that are damaged or seriously deteriorated may have an adverse effect on the seismic performance of an existing building during a severe earthquake. The significance of the damage or deterioration must be evaluated with respect to both the existing condition and the proposed seismic strengthening of the building.

2.3.1.1 Timber

Common problems with timber members that require rehabilitation include termite attack, fungus ("dry rot" or "damp rot"), warping, splitting, checking due to shrinkage, strength degradation of fire-retardant plywood in areas where high temperatures exist, or other causes.

2.3.1.2 Unreinforced Masonry

The weakest element in older masonry usually is the mortar joint, particularly if significant amounts of lime were used in the mortar and the lime was subsequently leached out by exposure to the weather. Thus, cracks in masonry walls caused by differential settlement of the foundations or other causes generally will occur in the joints; however, well-bonded masonry occasionally will crack through the masonry unit.

2.3.1.3 Unreinforced Concrete

Unreinforced concrete may be subject to cracking, spalling, and disintegration. Cracking may be due to excessive drying shrinkage during the curing of the concrete or differential settlement of the foundations. Spalling can be caused by exposure to extreme temperatures or the reactive aggregates used in some western states. Disintegration or raveling of the concrete usually is caused by dirty or contaminated aggregates, old or defective cement, or contaminated water (e.g., water with a high salt or mineral content).

2.3.1.4 Reinforced Concrete or Masonry

Reinforced concrete and masonry are subject to the same types of deterioration and damage as unreinforced concrete and masonry. In addition, poor or cracked concrete or masonry may allow moisture and oxygen to penetrate to the steel reinforcement and initiate corrosion. The expansive nature of the corrosion byproducts can fracture the concrete or masonry and extend and accelerate the corrosion process.

2.3.1.5 Structural Steel

Poorly designed structural steel members may trap moisture from rainfall or condensation under conditions that promote corrosion and subsequent loss of section for the steel member. Even well-designed steel members exposed to a moist environment require periodic maintenance (i.e., painting or other corrosion protection) to maintain their effective load-bearing capacity. Light structural steel members (e.g., small columns or bracing members) in some installations may be subject to damage from heavy equipment or vehicles. While such damage may have no apparent detrimental effect on the vertical-load-resisting capacity of the steel member, its reserve capacity for resisting seismic forces may be seriously impaired.

2.3.2 REHABILITATION TECHNIQUES FOR DETERIORATED CONDITION OF STRUCTURAL MATERIALS

Structural materials that exhibit evidence of damage or deterioration require careful evaluation. Even if affected structural elements are to be rehabilitated or replaced, it is important that the factors contributing to the damage or deterioration be eliminated or minimized. For example, vulnerable steel framing can be protected from heavy equipment or vehicles by concrete curbs or concrete encasement, poorly drained steel members and connections can be modified or replaced so as to provide positive drainage, and steel framing in moist environments can be painted or covered with other corrosion-resistant coatings.

If the deterioration is not severe and the apparent causes have been mitigated, the engineer may decide to assign a reduced capacity to the structural member and to perform a revised evaluation of the need for rehabilitation and/or strengthening.